Probing $Zt\bar{t}$ couplings using Z boson polarization in ZZ production at hadron colliders

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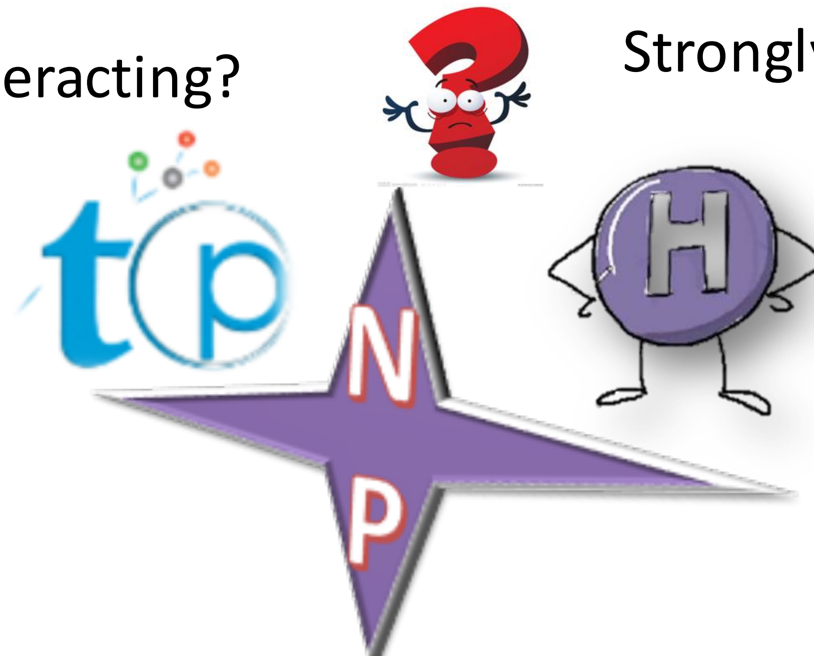
In collaboration with: Qing-Hong Cao , C.-P. Yuan and Ya Zhang

arXiv:2004.02031

Top quark as a probe of New Physics

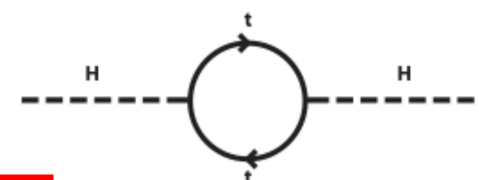
SUSY Little Higgs Composite .....

Weak interacting? Strongly interacting?



Electroweak symmetry breaking

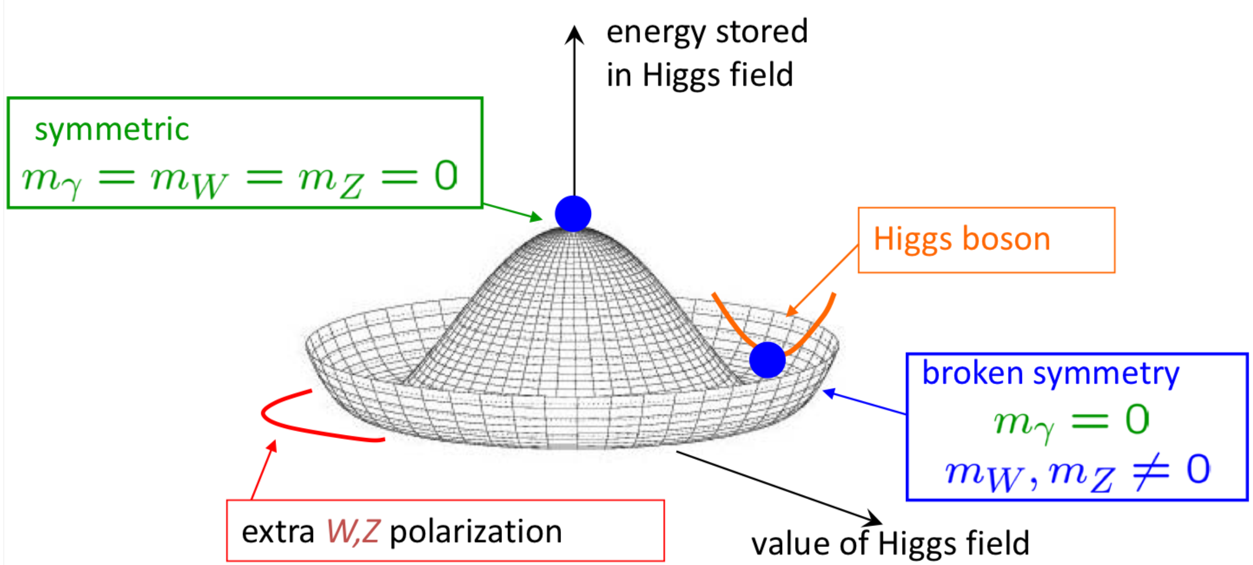
Naturalness hierarchy problem



Decay product of NP Resonances

Extra Gauge Bosons New Heavy Quarks Extra scalars

Top quark & EWSB

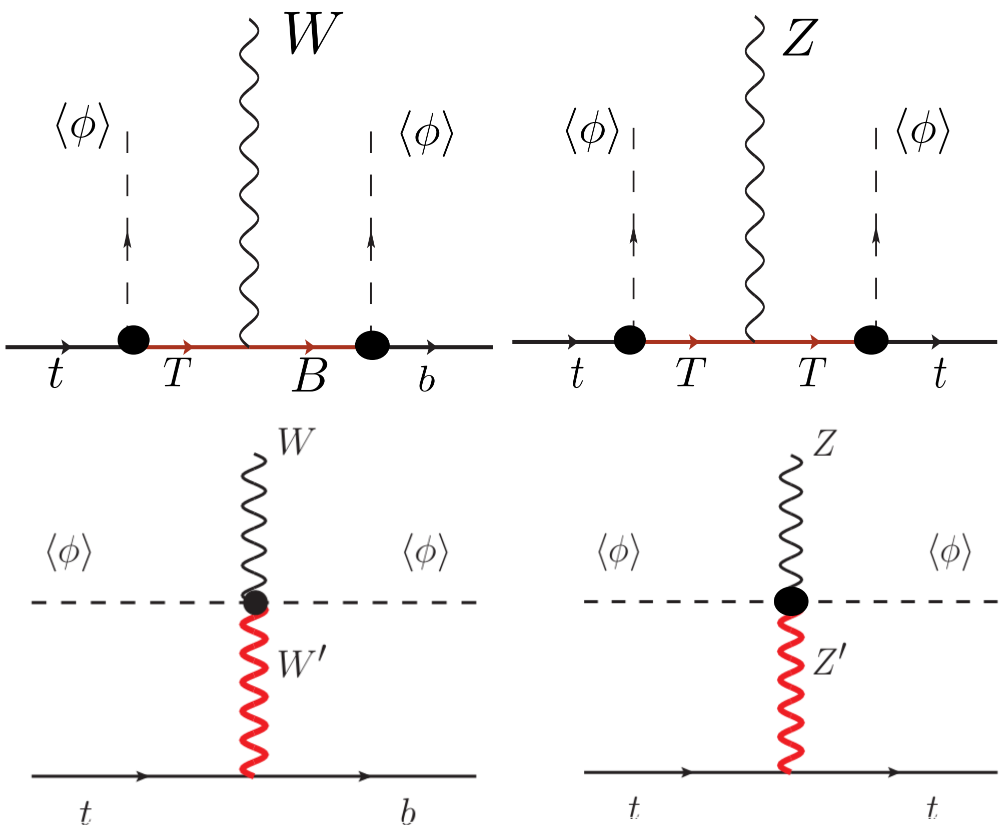


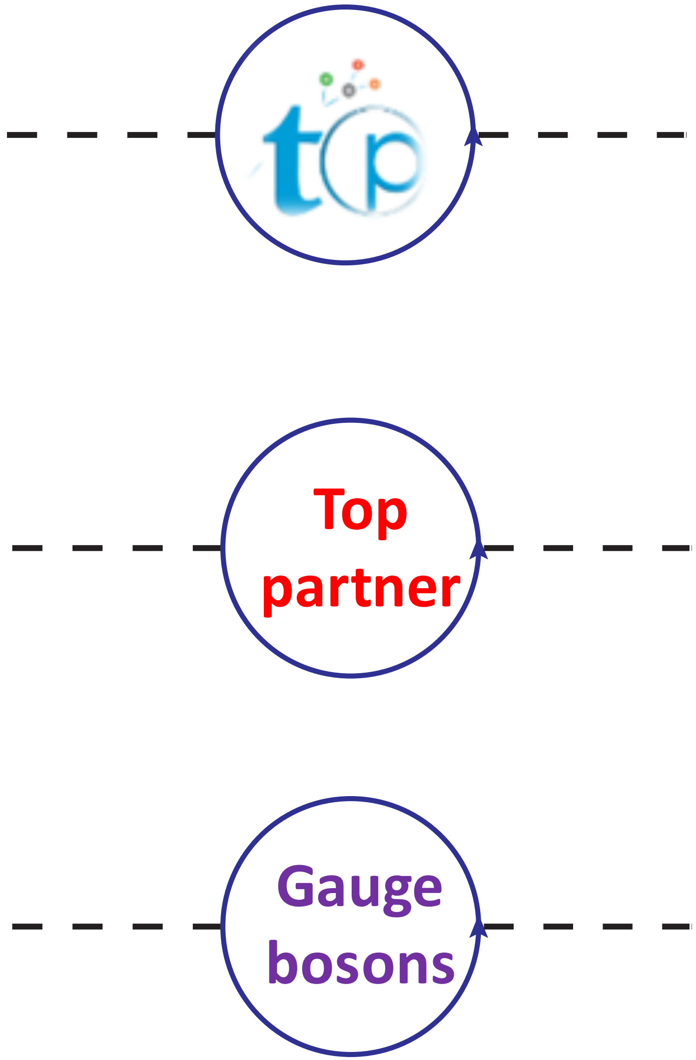
For example: in composite Higgs model

$$V = \beta \sin^4 \frac{h}{f} - \gamma \sin^2 \frac{h}{f}$$

Top quark and EWSB

$$V = \beta \sin^4 \frac{h}{f} - \gamma \sin^2 \frac{h}{f}$$

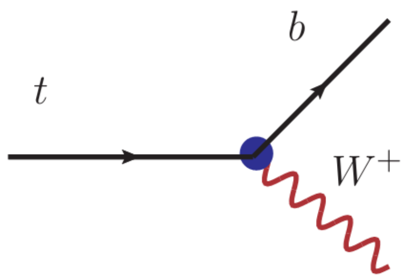


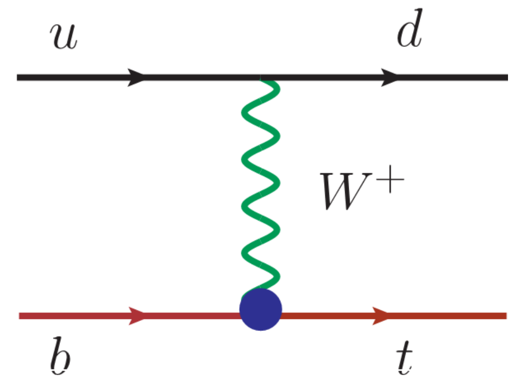


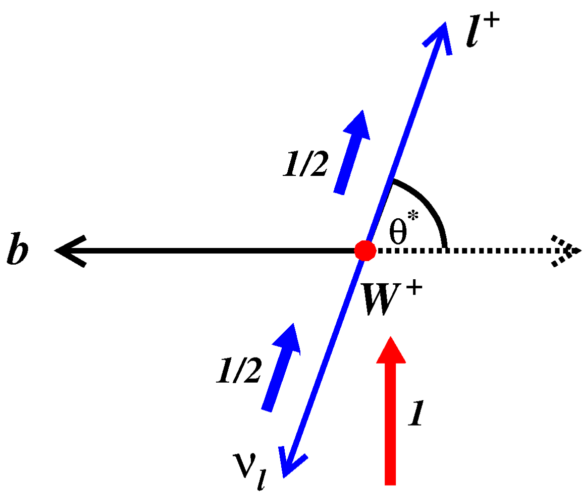
Top quark gauge couplings

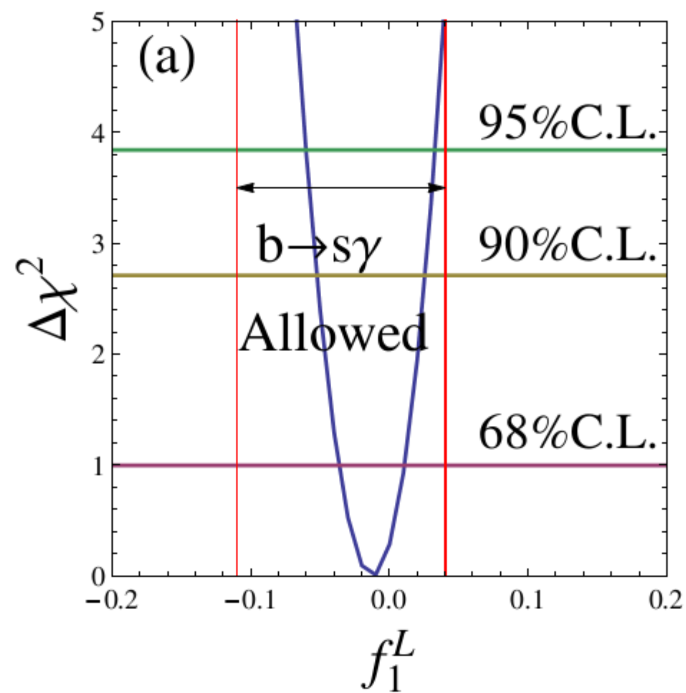
A. Charge current

Q.-H. Cao, B. Yan, J. H, Yu and C. Zhang, CPC41(2017)6,063101
E.L. Berger, Q.-H. Cao and I. Low, PRD80,074020(2009)









$$d^1_{1,-1} = \frac{1-\cos\theta}{2}, d^1_{1,1} = \frac{1+\cos\theta}{2} \quad d^1_{1,0} = -\frac{\sin\theta}{\sqrt{2}}$$

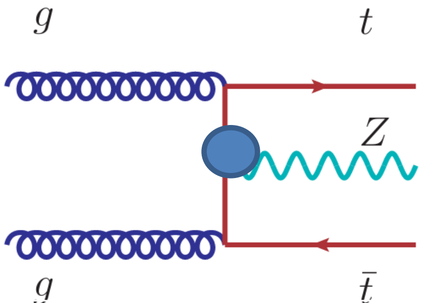
Top quark gauge couplings

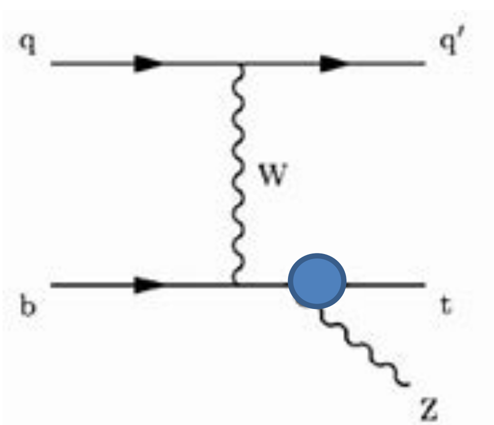
B. Neutral current

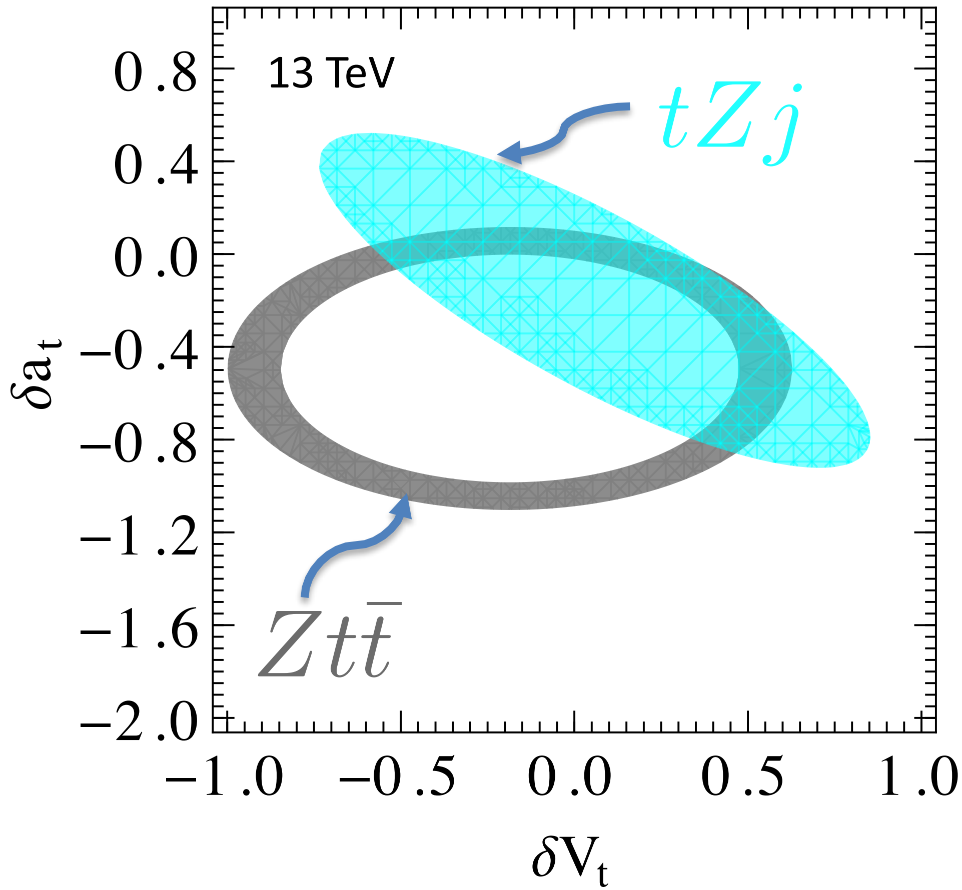
$$\mathcal{L} = \frac{g_W}{2c_W}\bar{t}(v_t - a_t\gamma_5)\gamma_\mu t$$

$$v_t^{\rm SM} = 0.35, \quad a_t^{\rm SM} = \frac{1}{2}$$

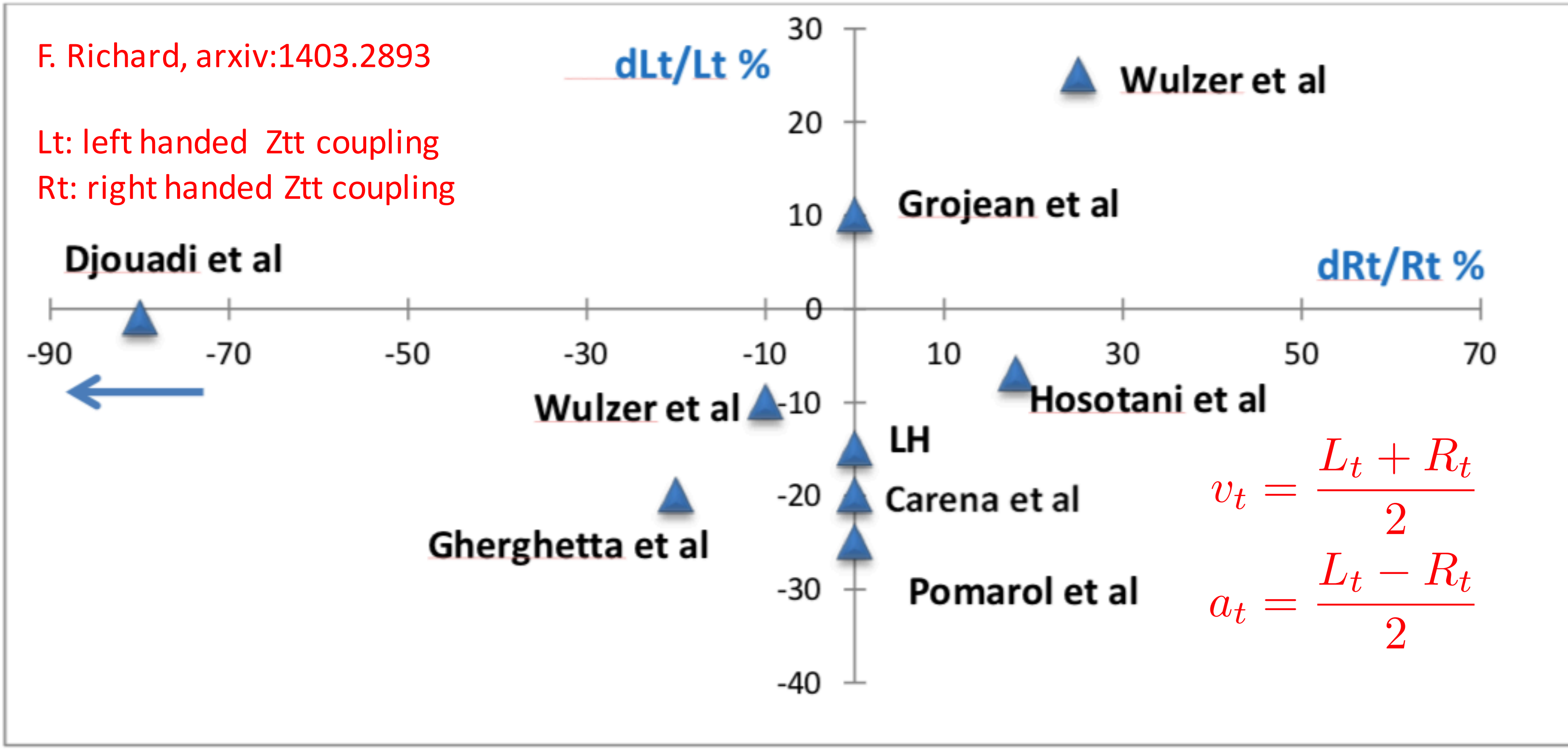
E.L. Berger, Q.-H. Cao and I. Low, PRD80,074020(2009)
R. Rontsch and M. Schulze, JHEP07,091(2014)
O. Bessidskaia Bylund et al, JHEP05,052(2016)







Top quark Neutral current & NP

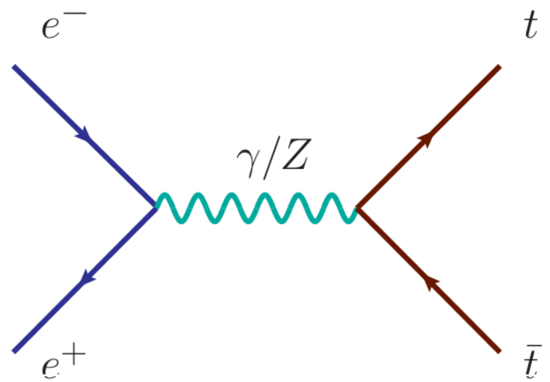


Distinguishing the vector and axial vector components of Ztt coupling=> different NP models

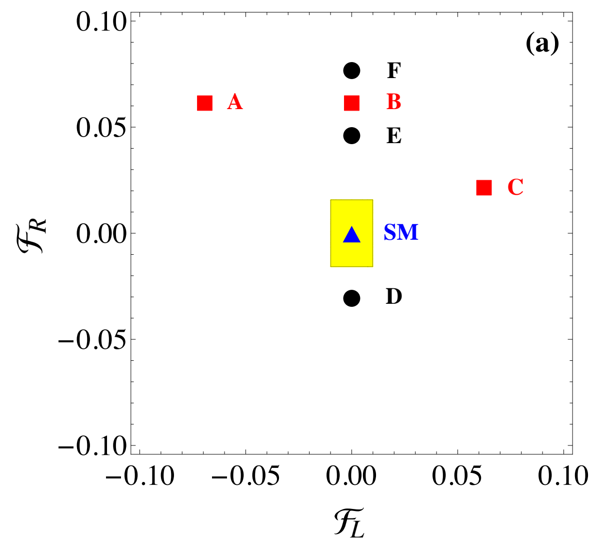
How to distinguish the top quark couplings

A, B and C: extra dimensional models

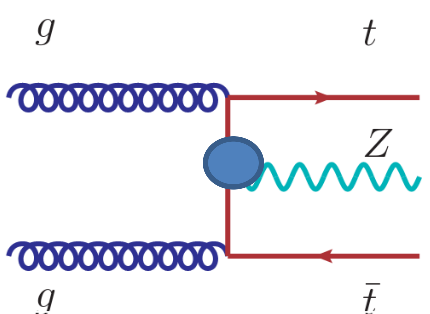
D, E and F: the composite models



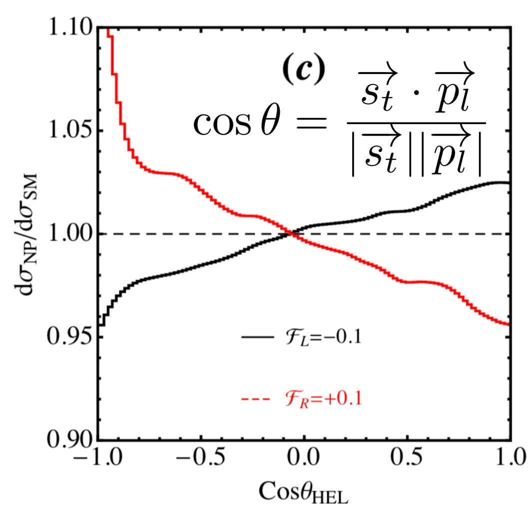
Q. H. Cao and B. Yan,PRD92,094018(2015)



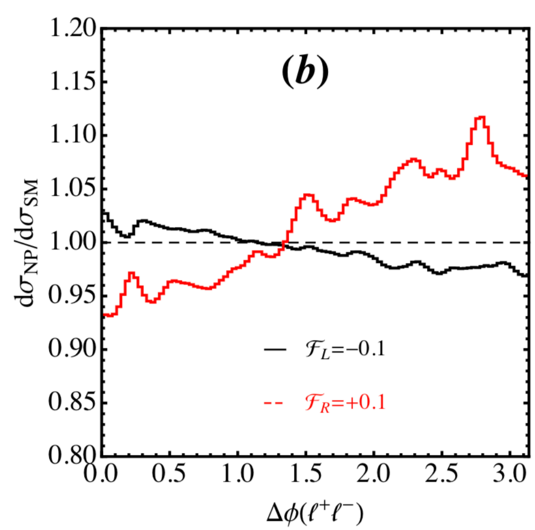
E. L. Berger, Q. H. Cao, I. Low, PRD80(2009)074020



A. Top quark Spin correlation



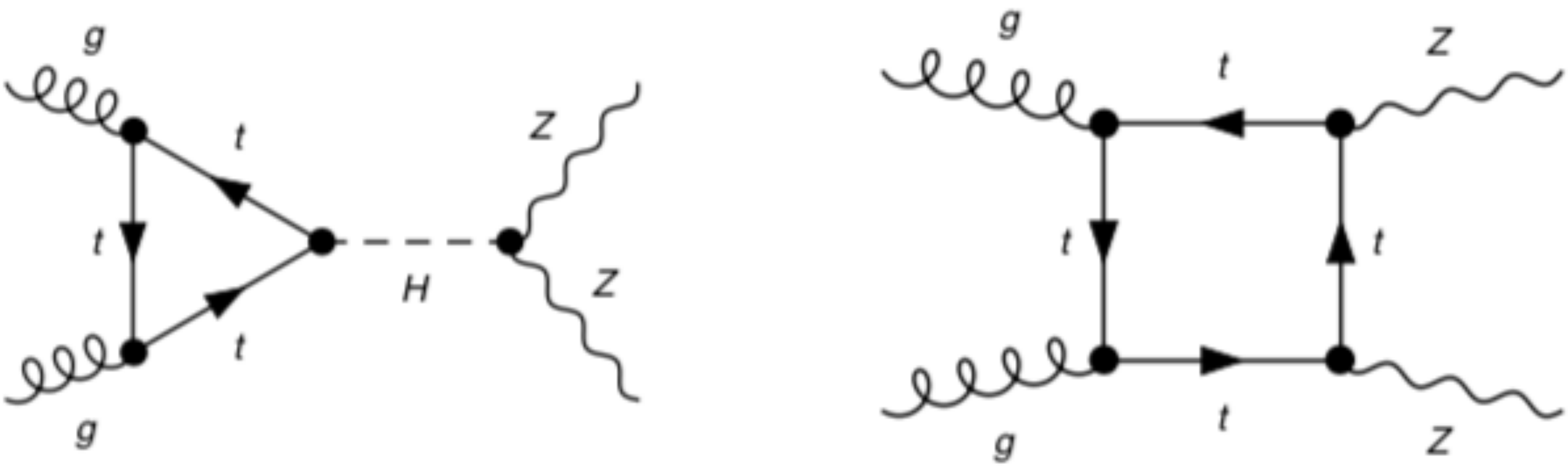
B. $\Delta\phi(\ell^+\ell^-)$



How to distinguish the top quark couplings

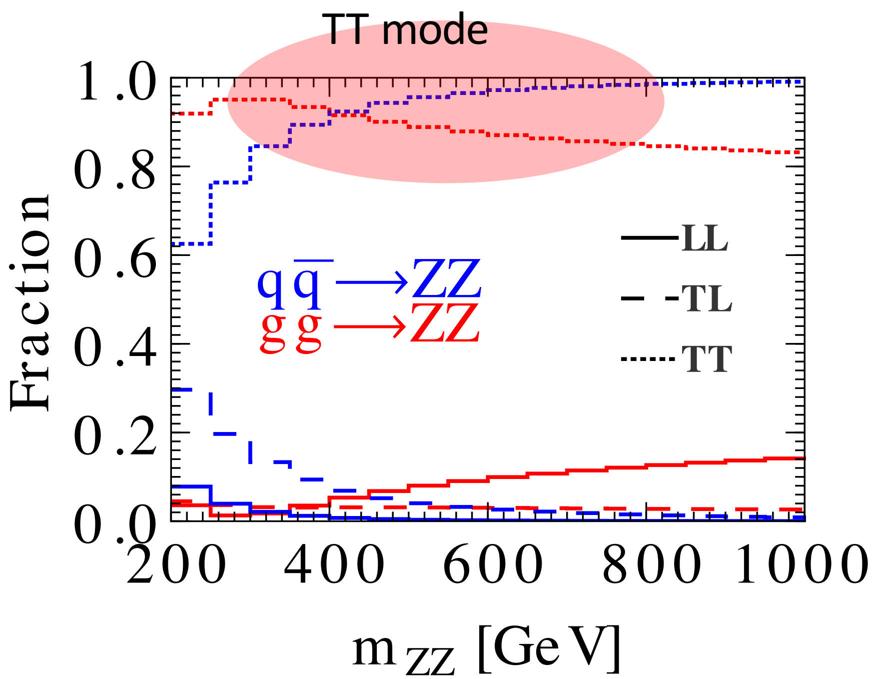
Other possibility:

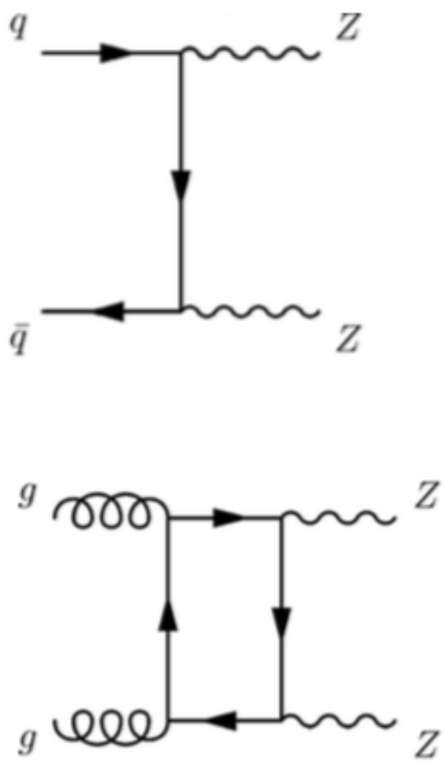
Q.-H. Cao, B. Yan, C.-P. Yuan and Ya Zhang, arxiv:2004.02031



Top quark coupling will change the polarizations of Z boson pair

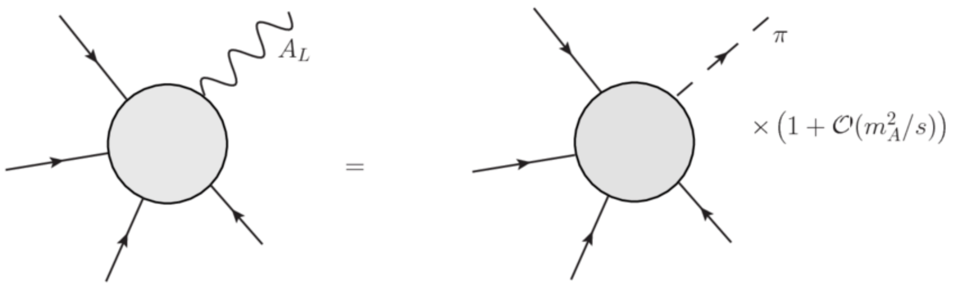
Polarization of ZZ scattering

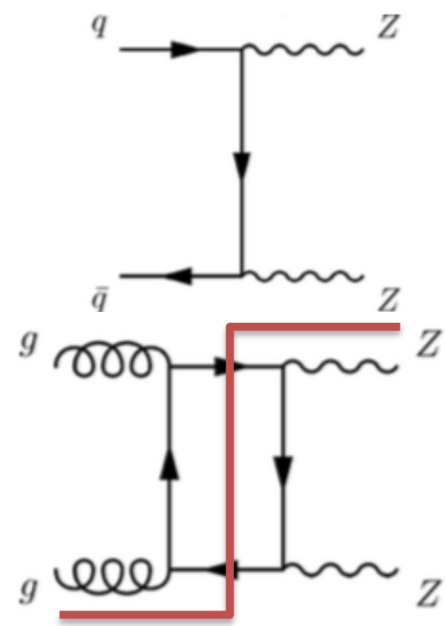




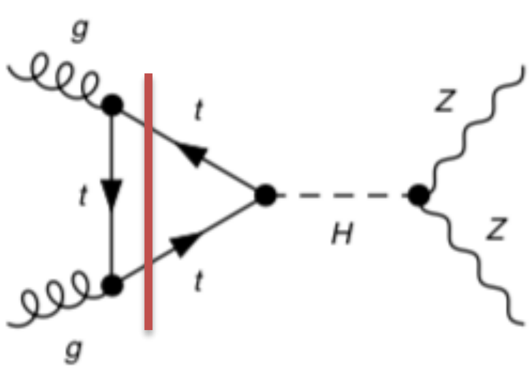
Both quark and gluon initial states are dominantly by the TT mode

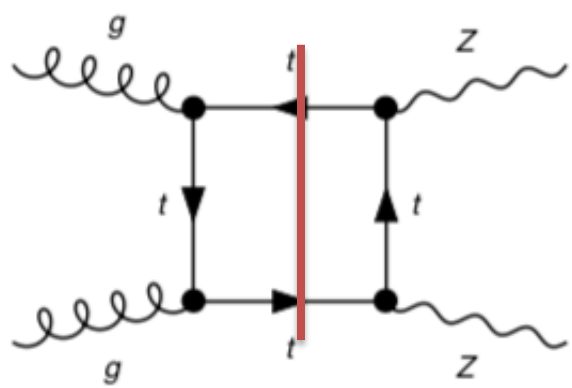
Goldstone equivalence theorem and Unitarity





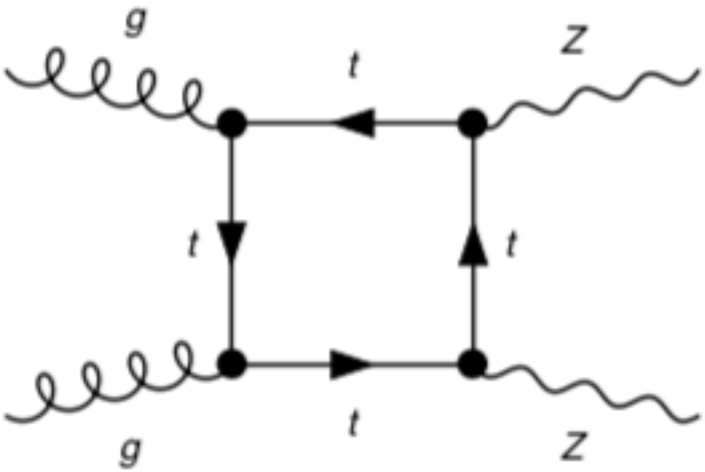
The light quark contribution to LL mode will be suppressed





There is a cancellation between the triangle and box diagrams due to the Unitarity

Axial current of top quark coupling



$$\mathcal{L} = \frac{g_W}{2c_W}\bar{q}(v_q - a_q\gamma_5)\gamma_\mu q$$

Energy Dependence in the high energy limit:

E. W. N. Glover and J.J. van der Bij, NPB321,561(1989)

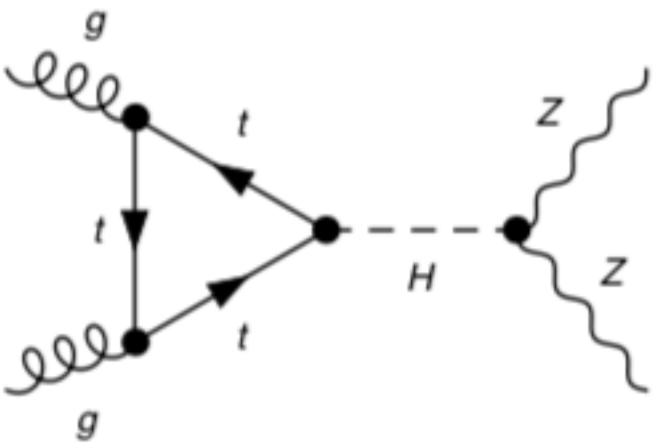
$$M^{\square}_{\lambda_1,\lambda_2,\lambda_3,\lambda_4} = \left(v_q^2 + a_q^2\right) A_{\lambda_1,\lambda_2,\lambda_3,\lambda_4} + \left(v_q^2 - a_q^2\right) B_{\lambda_1,\lambda_2,\lambda_3,\lambda_4} + a_q^2 C_{\lambda_1,\lambda_2,\lambda_3,\lambda_4}$$

$\hat{s} = -\hat{t}/2 = -\hat{u}/2 \gg m_t, m_z$

$$A \sim \text{Constant},$$
$$B \sim 0,$$
$$C_{\pm,\pm,0,0} \sim -\frac{m_t^2}{m_Z^2}\left[\log^2\left(\frac{\hat{s}}{m_t^2}\right) - 2i\pi\log\left(\frac{\hat{s}}{m_t^2}\right)\right]$$

Axial current is not conserved for massive top quark.

Unitarity of Gluon Fusion



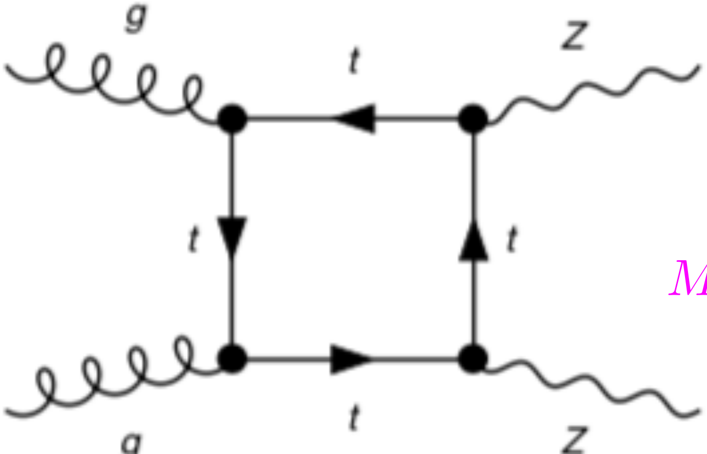
Energy Dependence in the high energy limit:

$$M^{\triangle}_{\pm,\pm,0,0} \sim \frac{m_t^2}{4m_Z^2}\left[\log^2\left(\frac{\hat{s}}{m_t^2}\right) - 2i\pi \log\left(\frac{\hat{s}}{m_t^2}\right)\right].$$

Unitarity + Axial current is not conserved

Strong cancelation

$$a_t = \frac{1}{2} \quad \text{(SM)}$$

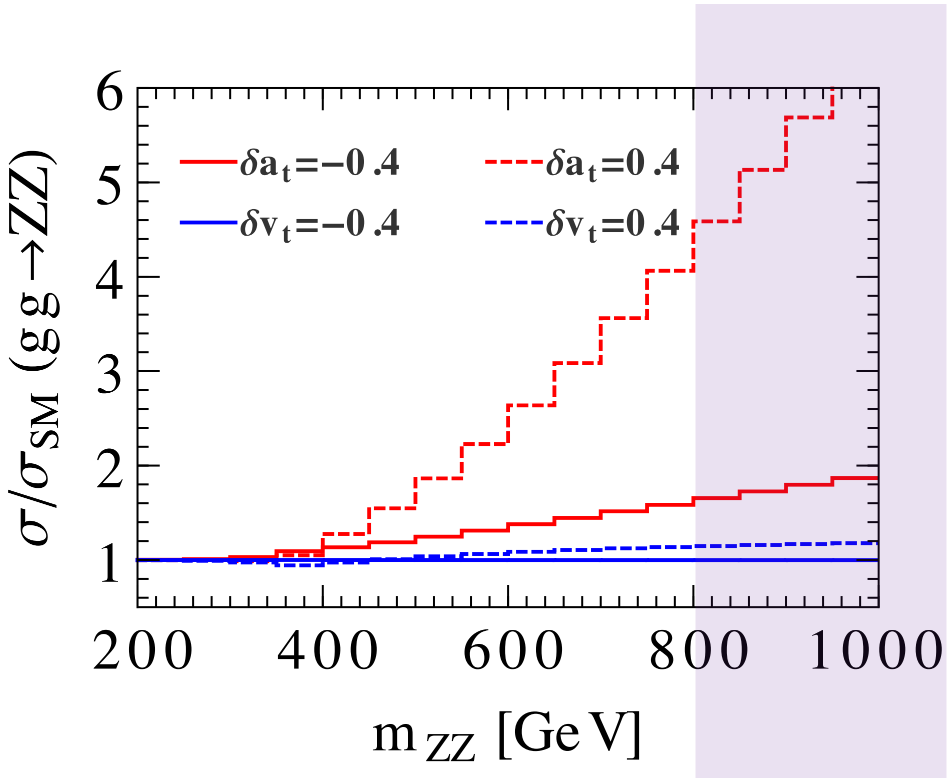


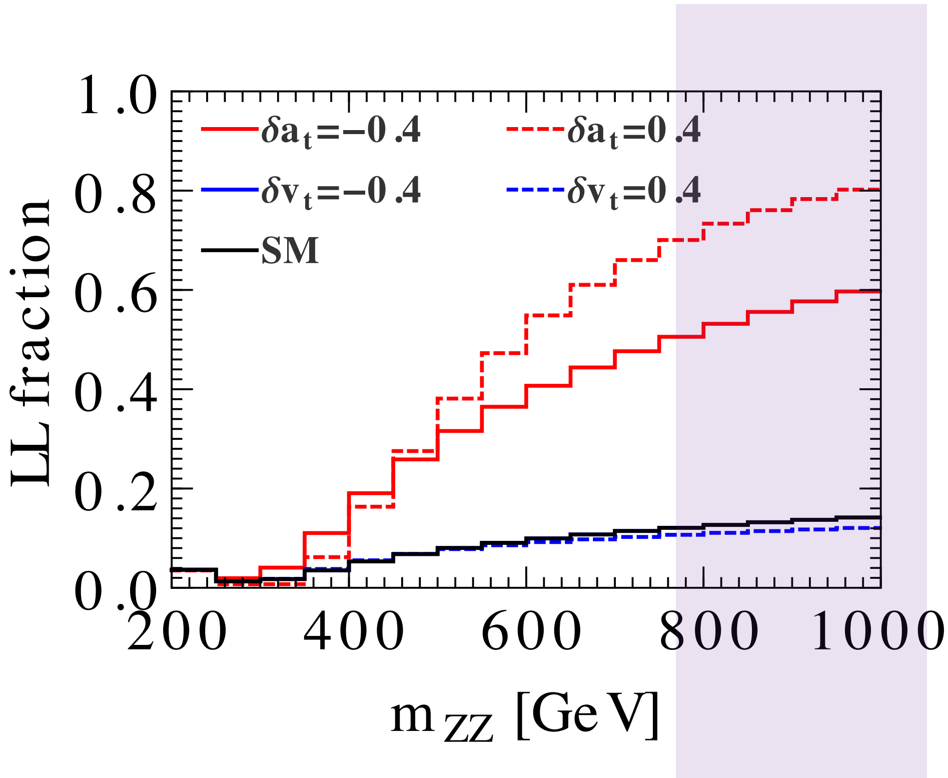
$$M^{\square}_{\pm,\pm,0,0} \sim -a_t^2\frac{m_t^2}{m_Z^2}\left[\log^2\left(\frac{\hat{s}}{m_t^2}\right) - 2i\pi \log\left(\frac{\hat{s}}{m_t^2}\right)\right].$$

LL mode is sensitive to the axial current of top quark

Cross section and polarization

$$\delta v_t = v_t - v_t^{\rm SM}, \quad \delta a_t = a_t - a_t^{\rm SM}.$$



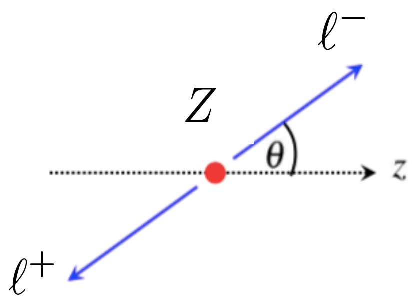


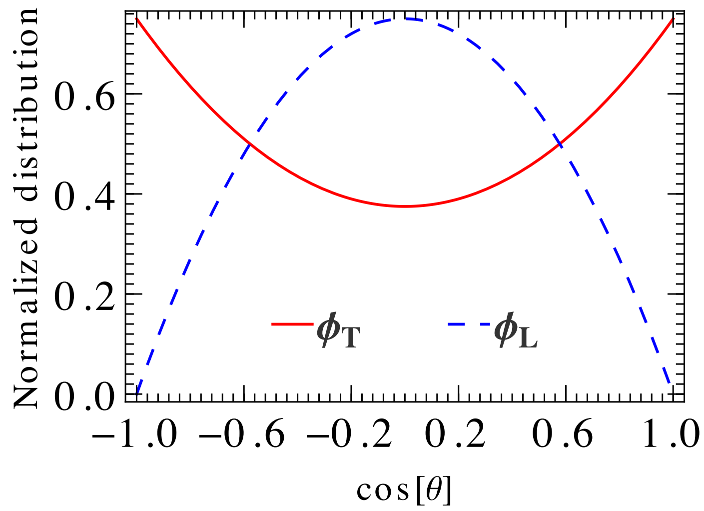
The axial current of top quark will change the total cross section and LL fraction remarkably

How to measure LL mode at the LHC?

Polarization of Z bosons in ZZ scattering

Z boson rest frame:



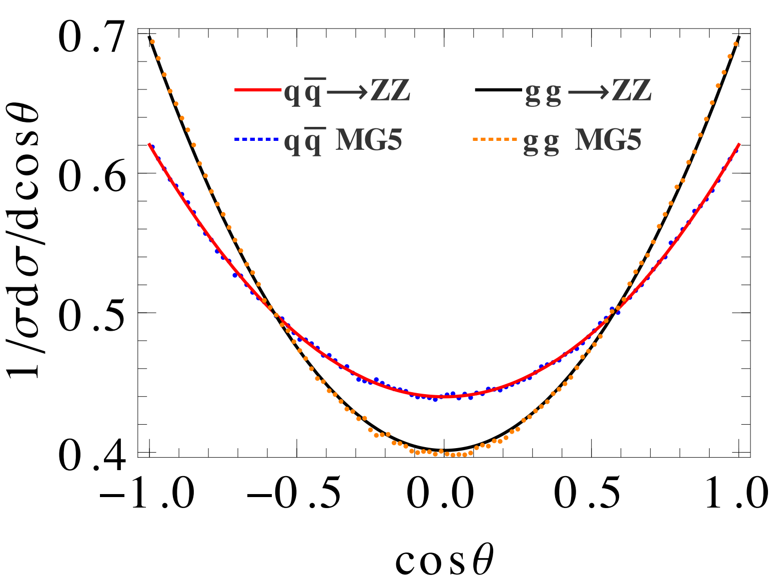


Transverse:

$$\phi_T = \frac{3}{8}(1 + \cos\theta^2)$$

Longitudinal:

$$\phi_L = \frac{3}{4}(1 - \cos\theta^2)$$



$$\frac{d\sigma}{\sigma d\cos\theta} = f_L\phi_L + f_T\phi_T$$

ZZ polarization fractions: $f_{L,T}$

The theoretical calculation agrees with MG5 very well

Collider Simulation@13 TeV LHC

$|\eta_l| < 2.5, P_{T\ell} > 15$ GeV

$80 < m_{\ell^+\ell^-} < 100$ GeV

$m_{4\ell} > 600$ GeV

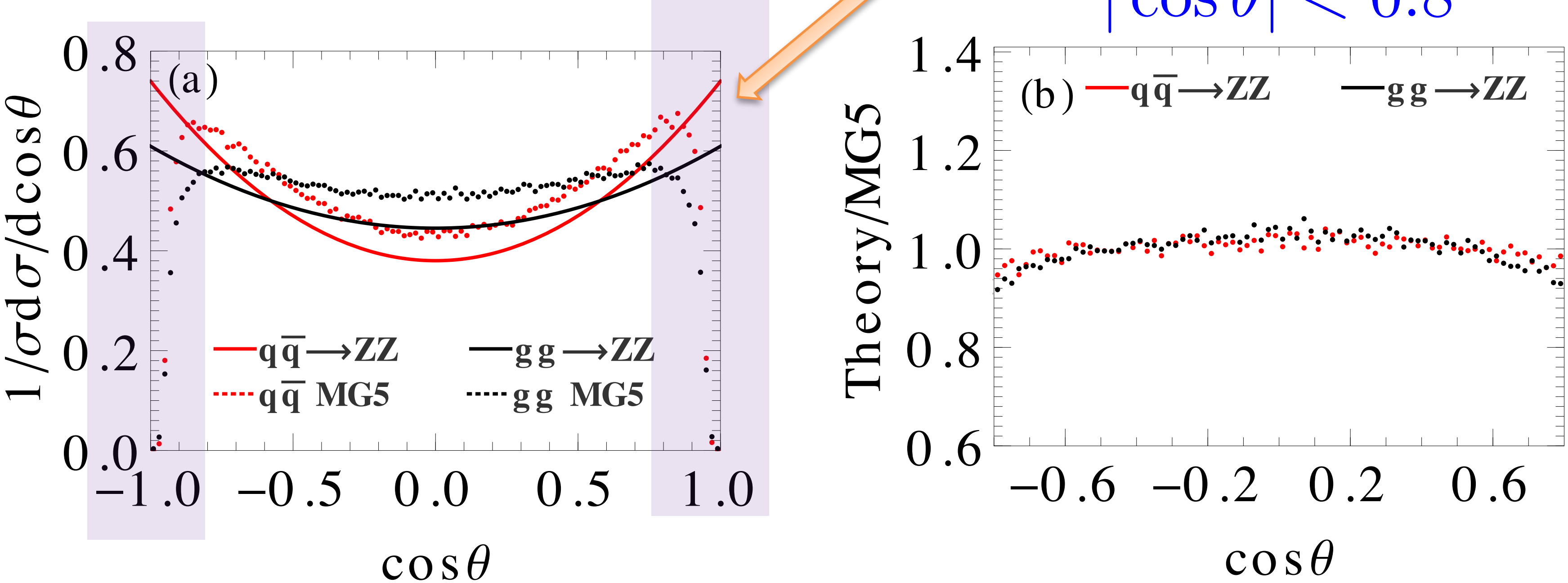
Effectively

$|\eta_Z| < 2.$

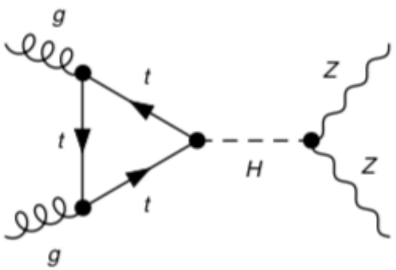
$m_{ZZ} > 600$ GeV

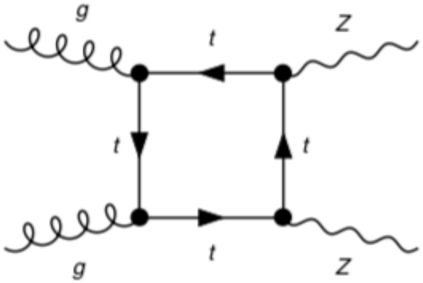
Detector effects for the edges

$|\cos\theta| < 0.8$

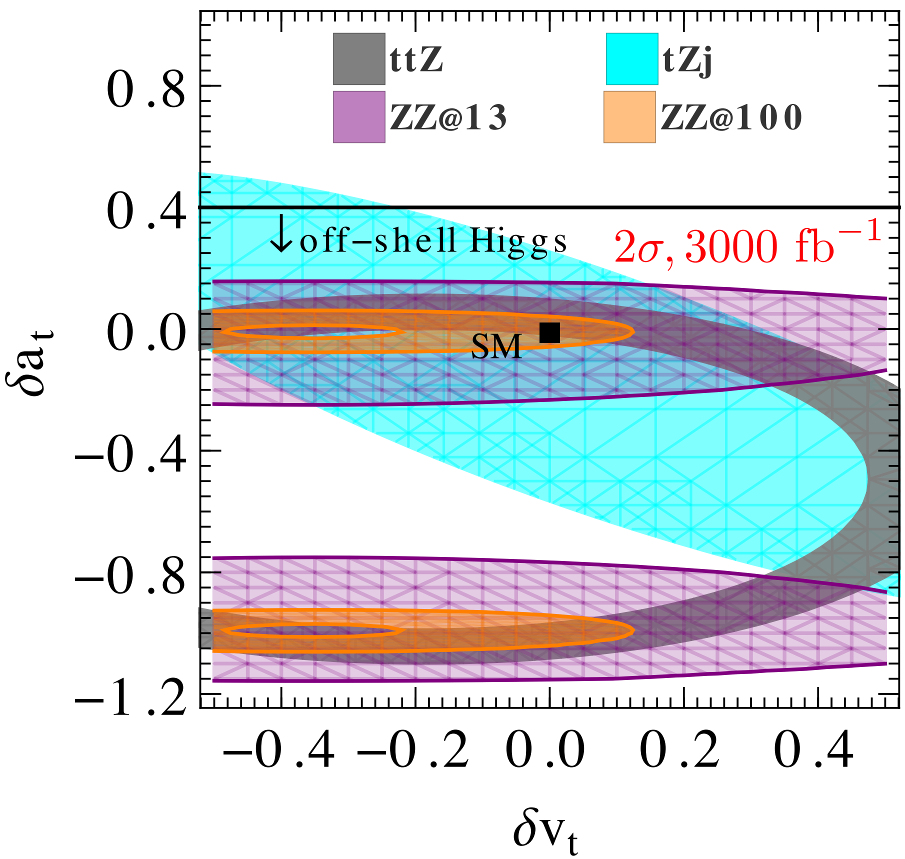


ZZ polarization and top quark





$$\mathcal{L} = \frac{g_W}{2c_W}\bar{t}(v_t - a_t\gamma_5)\gamma_\mu t$$



A. ZZ polarization only sensitive to the axial-vector component of Ztt coupling;

B. ZZ production is complementary to the Ztt and Ztj productions in measurements of the Ztt coupling.

Thank you!

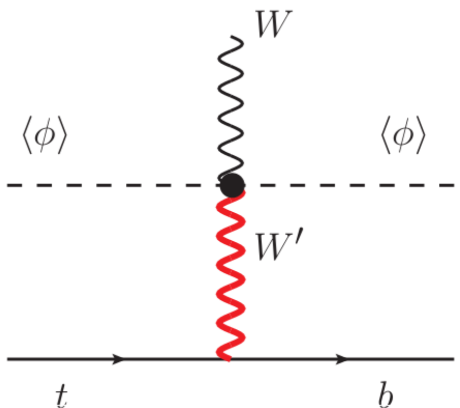
Top quark gauge couplings

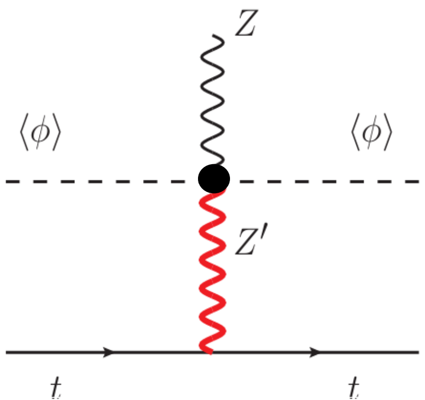
$$O_{\phi q}^{(1)} = i(\phi^+ D_\mu \phi)(\bar{q}\gamma^\mu q) \qquad O_{\phi\phi} = i(\tilde{\phi}^+ D_\mu \phi)(\bar{t}_R \gamma^\mu b_R)$$

$$O_{\phi t} = i(\phi^+ D_\mu \phi)(\bar{t}_R \gamma^\mu t_R) \qquad O_{\phi q}^{(3)} = i(\phi^+ \tau^I D_\mu \phi)(\bar{q}\gamma^\mu \tau^I q)$$

$$q = \begin{pmatrix} t \\ b \end{pmatrix}_L \qquad \tilde{\phi} = i\tau^2 \phi^*$$

E. L. Berger, Qing-Hong Cao, Ian Low, Phys.Rev.D80:074020(2009)

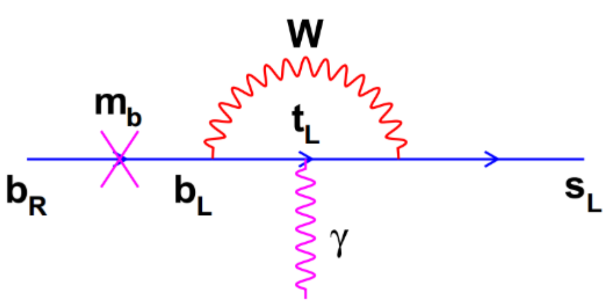


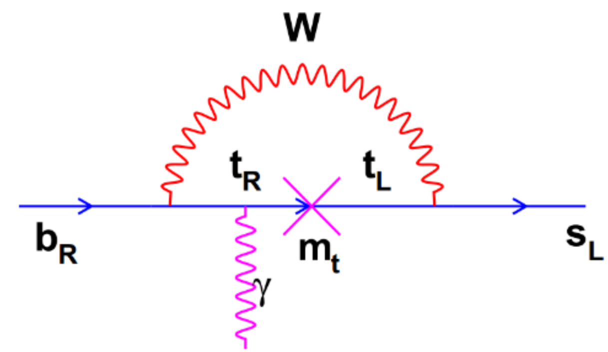


Top quark gauge couplings

$$-8\times10^{-4} \le \frac{c_{\phi\phi}v^2}{2\Lambda^2} \le 2.1\times10^{-3}$$

$$O_{Wtb} = \frac{c_{\phi q}^{(3)}v^2}{\Lambda^2}\frac{g}{\sqrt{2}}W_\mu^+\bar{t}_L\gamma^\mu b_L + \frac{c_{\phi\phi}v^2}{2\Lambda^2}\frac{g}{\sqrt{2}}W_\mu^+\bar{t}_R\gamma^\mu b_R + h.c.$$





Q.-H. Cao, B. Yan, J. H, Yu and C. Zhang, CPC41(2017)6,063101

$$O_{Ztt} = \frac{\left(c_{\phi q}^{(3)} - c_{\phi q}^{(1)}\right)v^2}{\Lambda^2}\frac{g}{2c_W}Z_\mu\bar{t}_L\gamma^\mu t_L - \frac{c_{\phi t}v^2}{2\Lambda^2}\frac{g}{2c_W}Z_\mu\bar{t}_R\gamma^\mu t_R$$